

Assessment of ecological and human health concerns associated with heavy metal poisoning in the sediments of Western St. Martin's Island, Bangladesh

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Abstract

St. Martin's Island (SMI) was designated an Ecologically Critical Area by the Bangladesh government in 1999 to preserve its biodiversity. Heavy metals (HMs) pollution is a critical environmental problem, driven primarily by anthropogenic activities, that causes various environmental impacts, including the contamination of marine resources. This study aimed to investigate the presence of HMs in marine sediments and evaluate the potential risks they pose to the marine environment and human health (adults and children). Atomic Absorption Spectrometry was used to assess the HMs in composite sediment samples collected from 12 sampling sites along the west coast of SMI. The average ($\pm$ SD) HM concentrations (mg/kg) found, in descending order, were Mn (317.58 ± 48.1) > Fe (168.42 ± 35.46) > Zn (31.17 ± 6.34) > Ni (24.17 ± 6.41) > Cr (12.17 ± 3.18) > Pb (6.52 ± 1.03) > Cu (5.16 ± 0.94). All detected HMs concentrations were below the allowable levels and considerably lower than those reported in other studies. The Risk Index (RI) results suggest that the marine ecosystem along the west coast of SMI did not surpass the low-moderate risk line (ranging from 0.23 to 6.18 with a mean of 4.68). Furthermore, the sediment quality indices used, including the contamination factor, geo-accumulation index, and pollution load index, indicated that metal contamination levels were within acceptable limits and did not adversely affect sediment quality. Human health risk assessment demonstrated that for each age group of the SMI population, the non-carcinogenic Hazard Index (HI) was significantly below the threshold limit ($HI < 1$), indicating low risk. In addition, the total carcinogenic risk was below



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the risk threshold range (10^{-4} to 10^{-6}). Safeguarding the health of the SMI population and the integrity of the marine ecosystem will require HM monitoring and the execution of strict regulations to reduce HM pollution.

Key words: Ecologically Critical Area, Ecological and human health risk assessment, Heavy metals, Sediment, St. Martin's Island

Introduction

The contamination of the marine environment by heavy metals (**HMs**) has grown in importance over the past several decades (Ali et al. 2022a, b; Bhuyan et al. 2023). In general, the rise in contaminants is a result of both the lack of clear maritime environmental regulations and the rise of contamination from human-caused actions including industry, agriculture, and urbanization (Bhuyan and Bakar 2017; Bat et al. 2022). Tourism on St. Martin's Island (**SMI**) has emerged as one of the key factors in the deterioration of the island's natural environment and the contamination of marine habitats. Many pollutants linked to raw sewage discharged into the sea contain contaminants that interact with sediments and marine ecosystems (Bhuyan et al. 2019; Bhuyan et al. 2023). Sewage discharges contaminate coastal waters with dangerous pathogens and substances such as HMs, oils, and hydrocarbons, which interact with marine biota and enter the human food chains (Ardila et al. 2022; Gopal et al. 2022).

Coastal zones are the transition zones between the terrestrial and marine ecosystems. The physiochemical and biological interactions occurring on beaches have a significant impact on the fate and transport of HMs that depend on complex physiochemical conditions such as oxidation-reduction potential (Eh) and pH, as well as the presence of flora and fauna (El Zokm 2023). Beaches are sensitive and transient systems easily damaged by natural and anthropogenic activities, such as riverine and atmospheric inputs, coastal and seafloor erosion, biological activities, and intense human activities such as tourism development (Schmitt and Chaumillon 2023). Marine sediments are important sinks for HMs which originate from land-based sources. Enriched HMs in coastal regions are not only endangering tidal organisms directly, but they also threaten human health through various food chains (Tripathi et al. 2021).

Textiles, coal and energy plants, cement plants, tanneries, and shipbreaking/recycling are among the land-based metal-polluting industries that have been growing steadily over the past few decades as these businesses have emerged as a significant contributor to both macro and micro perspectives of economic growth (Sharifuzzaman et al. 2016). In certain developing nations, the shipbreaking industry has become extremely profitable because of low labor prices, favorable geographic locations, and a lack of adherence to environmental and safety regulations (Sarraf et al. 2010). Even though disassembling ships exposes a significant amount of HMs into the environment, the scraps are utilized as raw materials for rerolling mills and other applications, indicating both possible benefits and risks for an increasingly globalized economy. Although human activity has had a significant impact on more than 40% of the world's oceans, the harshest effects are being felt in coastal regions.

Coastal waters along the southeastern coast of Bangladesh have become increasingly contaminated by urban runoff, agricultural waste, and industrial pollutants, which enter the major river systems and are eventually discharged into the marine environment (Bhuyan et al. 2019). The shallow waters surrounding SMI are highly productive, making the island a biodiversity hotspot in Bangladesh (Biswas et al. 2021). However, uncontrolled coastal development is having a negative impact on SMI's marine resource base. The unregulated expansion of the tourism industry has played a significant role in this rapid development. This growth may threaten the island's marine biodiversity, ecological resources, and local population (Bhuyan et al. 2023). During the high tourist season (November to March), six large ships and numerous small boats from Teknaf transport approximately 3,000 tourists per day to the island. On weekends, more than 5,000 tourists stay on SMI (Rashid 2008). In line with global trends, increased tourism is likely to result in higher levels of environmental degradation and pollution (Dogru et al. 2020). The rapid growth of tourism on SMI may adversely affect coastal water quality through increased discharge of wastewater containing various contaminants (Jafarabadi et al. 2017). HMs and other pollutants have already been detected in the island's water and surface sediments, as reported by Sarker et al. (2020). However, comprehensive studies on HM distribution in the surface sediments of coastal waters around SMI remain limited. To date, the only focused investigation has been conducted on the eastern part of the island by Bhuyan et al. (2023). Given the potential for HM contamination to harm local residents, tourists, and marine biodiversity, further research is urgently needed. This study aims to assess whether current HM concentrations in coastal sediments around Western SMI present a potential risk to public health and marine biodiversity.

Materials and methods

Study area

The coordinates of St. Martin's Island (SMI) are between 20°34'N and 20°39'N latitude, and 92°18'E and 92°21'E longitude. This study was conducted in SMI, located in the southernmost part of Bangladesh in the northeastern Bay of Bengal, about 9 km south of the Teknaf peninsula and approximately 8 km off the west coast of Myanmar (Fig. 1). The area of SMI is roughly 5–6 km². About 250 years ago, Arabian traders arrived on the island and named it Jazira, but today it is locally known as Narikel Jinjira. The majority of the 3,700 islanders that live on the island today depend on fishing. Rice and coconut are the other two dietary sources (Ghose and Hossain 2020).

SMI is surrounded by a sedimentary rocky reef. Marine algae are plentiful on the reef and are often harvested, dried, and sold to Myanmar (Hossain et al. 2007). Some areas of the intertidal rocky reef have been colonized by mangroves, while the intertidal pools are home to corals and other benthic invertebrates and fish. SMI's coastal waters are home to 240 species of fish, 240 species of seaweed, 187 species of mollusks, 66 species of coral, 120 species of birds, and 29 species of mammals (Thompson and Islam 2010). The area surrounding SMI received a Marine Protected Area designation in 2022 (Wildlife Conservation Society 2022; Hossen and Sultana 2024).

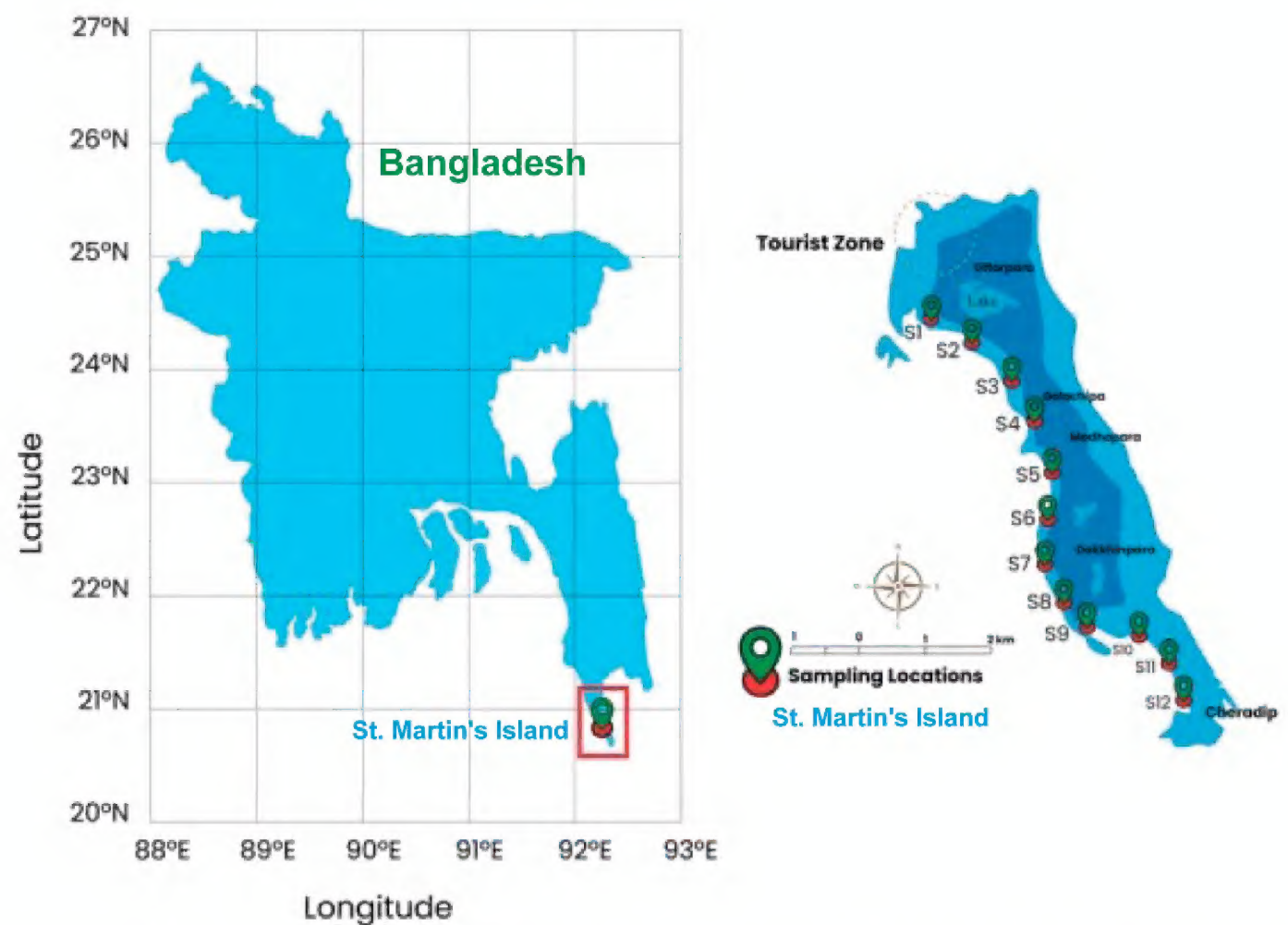


Figure 1. Map showing the location of St. Martin's Island in Bangladesh, and the location of sampling sites along the west coast of the island.

Geological setting

Located in the northeastern segment of the Indian Ocean, the triangular Bay of Bengal stands as the largest tropical semi-enclosed bay globally (Yousuf 2023). SMI is characterized by its flat terrain, with a maximum elevation of about 3.6 meters above mean sea level (Hossen and Sultana 2023). To the southwest of SMI, the sea is shallower than the 9.66 km channel connecting the island with the mainland (Bhuyan et al. 2023).

Geologically, the island is not a coral island and is a sedimentary continental island located on an anticlinal uplift (Tomascik et al. 2020; Tomascik 2021). The anticline's axis extends partly along the west coast of Dakshinpara. The anticlines exposed portion of the island trends from north-northeast to south-south-east. A fault runs nearly similar to the axis along the northwestern coastline. SMI's limestone comprises coral aggregates and layers of molluscan coquina. This shelly limestone, known for its high permeability, forms the aquifer, especially under the alluvial layers. Freshwater sources are found predominantly in this shelly limestone and the recent coastal sands (Banglapedia 2021).

Collection and preservation of samples

To assess HM concentrations in SMI's sediment, a total of 12 sediment samples were collected from 12 sampling sites. Three samples were collected from each site making it one composite sample (Fig. 1). A 500 g sample was collected using Ekman dredge from the study site. Composite samples were considered instead of grab samples to obtain a more representative and accurate assessment of the overall conditions or characteristics of a specific sample (Petersen et al. 2004). The samples were then stored in airtight polyethylene bags and transported to the Bangladesh Council of Scientific and Industrial Research laboratory,

Chittagong, Bangladesh. The samples were dried in an oven at 45 °C for 48 hours. Once air-dried, they were pulverized into a fine powder using a mortar and pestle, passed through a 106 µm mesh, and then transferred to a polycarbonate vial. After being tagged, each vial was put in a desiccator to be examined for metals.

Digestion, analysis, and quality assurance of samples

Approximately 2 g sample was digested at 130 °C for five hours until almost dry, using a mixture of 10 ml of concentrated HNO₃ and 5 ml of concentrated HClO₄. The resulting solution was filtered using filter paper, washed with diluted HNO₃ (1/10 M concentration), and then diluted to a final volume of 100 mL in a standardized volumetric flask. This preparation was for the metal analysis, with a clear solution indicating complete digestion (Bhuyan et al. 2019; Bhuyan et al. 2023).

An atomic absorption spectrophotometer (model no. iCE 3300, Thermo Scientific) was used to analyze all samples for Cr, Cu, Ni, Pb, Mn, Zn, and Fe validated following the recommendations of EC567/2002. The prerequisites for using Atomic Absorption Spectroscopy to determine the presence of HMs in samples are in Table 1.

Table 1. Analytical specifications for AAS-based heavy metals analysis (Bhuyan et al. 2023).

Heavy metals	Wave-length (nm)	Lamp-current (mA)	Slit (nm)	Detection limit (mg/kg)	Calibration range (mg/kg)
Cr	357.90	12.0	0.50	0.25–2.00	AAS-Flame
Cu	324.80	5.0	0.50	0.25–2.00	
Ni	232.00	15.0	0.20	0.25–2.00	
Mn	279.50	12.0	0.20	0.25–2.00	
Zn	213.90	10.0	0.20	0.25–2.00	
Pb	217.00	10.0	0.50	0.25–2.00	
Fe	248.30	15.0	0.20	0.25–2.00	

Certified reference materials from Sigma Aldrich were applied to calculate equipment calibration curves for HM analysis. Deionized water was used throughout the analysis. Glassware used in the analyses was cleaned with 20 percent HNO₃ and then repeatedly rinsed with deionized water and oven-dried.

Contamination level assessment of sediments

Geoaccumulation index (Igeo)

Igeo is an essential environmental tool for determining the degree of pollution in sets of soil samples and differentiating between natural and man-made HM sources. The following formula is used to determine the Igeo:

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5B_n} \right)$$

In this equation, *C_n* is the measured concentration of a metal (*n*) in the sediment samples. As there is no local corresponding *B_n* value of the metal contents, *B_n* from Turekian and Wedepohl (1961) was used for the geochemistry

background concentration of these metals in local sediments. Factor 1.5 is used for correcting the background matrix correlation factor, considering lithogenic influences. Müller (1981) established seven classification levels for the Igeo index, as shown in Table 2.

Table 2. I_{geo} Index classes for sediment quality evaluation.

Classification	Contamination degree
I _{geo} ≤ 0	Almost unpolluted
0 < I _{geo} ≤ 1	From completely uncontaminated to somewhat polluted
1 < I _{geo} ≤ 2	Polluted to a moderate degree
2 < I _{geo} ≤ 3	Highly to moderately polluted
3 < I _{geo} ≤ 4	Heavily polluted
4 < I _{geo} ≤ 5	Heavily to extremely polluted
5 ≤ I _{geo}	Extremely polluted

Source: Müller (1981).

Contamination Factor (CF) and Pollution Load Index (PLI)

The region of interest is evaluated for contamination using the CF (Kadhum et al. 2016). The sediment quality in the study area was determined using the PLI.

$$CF = Cn_{(Sample)} / Bn_{(Shale)}$$

$$PLI = (CF1 \times CF2 \times CF3 \times \dots \times CFn)^{1/n}$$

CF is calculated by dividing the concentration of each element in the sediment by its respective background level, as outlined by Hakanson (1980). In the context of the PLI, ‘n’ represents the total number of elements analyzed. CF value < 1 indicates low pollution, whereas a value in the range 1–3 suggests moderate contamination. Loska et al. (1997) defined a CF in the range 3–6 as signifying considerable pollution, and a CF > 6 as indicating tremendously high pollution levels. Tomlinson et al. (1980) noted that a PLI = 0 depicts ideal quality, < 1 indicates an absence of pollution, and > 1 suggests the presence of pollution.

Potential Ecological Risk Index (PERI)

PERI is an index used in assessing ecological risks associated with HM contamination (Hakanson 1980). The index characterizes the productivity of aquatic habitats, reflecting their assumed sensitivity. This index is useful in evaluating the productivity of aquatic habitats, reflecting their assumed sensitivity. Liu et al. (2018a, b) noted that PERI is also applied to gauge sediment contamination levels. By incorporating toxicological and environmental factors, PERI represents a comprehensive evaluation of the potential ecological risk related to HM pollution (Bi et al. 2018). The calculation of PERI is as follows:

$$E_r^i = T_r^i \times CF$$

$$C_f^i = C_n^i / C_o^i$$

$$RI = \sum_{i=1}^n E_r^i$$

In these equations, E_r^i stands for the individual PERI, while RI indicates the total risk of all HMs in the sediment. T_r^i represents the toxic response factor (TRF) components responsible for sensitivity and toxicity (Yu et al. 2010; Ahmed et al. 2022). The sediment metal concentration and each element's background value are denoted by C_n^i and C_o^i , respectively, while the individual CF is represented by C_f^i . The PERI sediment values fall into the following categories.

$E_r^i > 150$, $R_i > 350$ – disastrous risk; $100 \leq E_r^i < 150$, $200 \leq R_i < 350$ – very high risk; $50 \leq E_r^i < 100$, $150 \leq R_i < 250$ – significant risk; $30 \leq E_r^i < 50$, $100 \leq R_i < 150$ – moderate risk; $E_r^i < 30$, $R_i < 100$ – low risk (Hakanson 1980; Kusin et al. 2018; Zhao et al. 2018a).

Human health risk assessment

The risk that exposure to soil-borne trace metals poses to human health was assessed following the chronic daily intake (CDI) method. Metal enters the human body via three distinct methods; hence CDIs may be calculated using these routes: skin, inhalation, and consumption (Kusin et al. 2018; USEPA 2011; Ahmed et al. 2021a):

$$CDI(\text{for inhalation}) = \frac{PM \times CS \times ET \times EF \times IR_{air} \times ED}{BW \times PEF \times AT}$$

$$CDI(\text{for dermal contact}) = \frac{CS \times SA \times AF \times EF \times ED \times ABS}{BW \times AT \times 10^6}$$

$$CDI(\text{for ingestion}) = \frac{CS \times EF \times ED \times IRS}{BW \times AT \times 10^6}$$

In this formula, CS denotes the concentration of trace metals in sediment. PM is the concentration of ambient particulate matter in the specified area, recorded at 0.146 mg/kg. EF represents the annual contact incidence over 350 days, while ET indicates a daily exposure frequency of 24 hours, as cited by Shen et al. (2014). The USEPA (2002, 2011) defines IR_{air} as the air inhalation rate, quantified at 20 m³/day, and ED as the duration of exposure, spanning 30 years. Body weight (BW) is categorized as 70 kg for adults and 15 kg for children (USEPA 2002). Furthermore, the USEPA (2002) suggests a Particulate Emission Factor (PEF) of 1.36×10⁹ m³/kg.

The average duration for exposure is calculated for non-carcinogens as 365×ED days and for carcinogens as 365×70 days. Regarding contact with soil, the surface area of the skin (SA) exposed is estimated at 5700 cm²/day for adults and 2800 cm²/day for children, as per USEPA (2011) guidelines. The soil adherence factor (AF) is set for adults at 0.07 mg/cm² and children at 0.2 mg/cm². To convert values from kilograms to milligrams, a conversion factor of 10⁶ is used. The USEPA (2011) also defines ABS as the rate of dermal absorption, with a rate for most elements of 0.001 and specifically for arsenic (As) as 0.03 while the ingestion rate (IRS) is noted as 100 mg/day.

Assessing non-carcinogenic risk (THQ)

The hazard quotient (HQ) methodology is utilized to assess the risk of non-carcinogenic effects arising from various levels of exposure to HMs. HQ is computed by comparing the CDI (CDI, in mg/kg/day) of a metal to its established reference dose (USEPA 1989). Both the HQ and the hazard index (HI) are calculated as follows (USEPA 2000):

$$HI = \sum_{i=1}^n HQ_k = HQ_{inhalation} + HQ_{dermal} + HQ_{ingestion}$$

Reference Dose (RfD) (in mg/kg/day) for key metals and their exposure routes, as per USEPA (2010), are: Hg (3.00E-04), Pb (3.50E-03), As (3.00E-04), Cr (3.00E-03), and Cd (1.00E-03). An HI greater than 1 suggests non-carcinogenic effects as a significant risk, necessitating mitigation measures (Saha et al. 2016; Zhao et al. 2018a).

Assessing carcinogenic risk

The estimation of lifetime cancer risk (CR) due to exposure to specific metal concentrations is conducted using the cancer slope factor (CSF) for each exposure route (USEPA 2000). The CSF standards for As, chromium (Cr), and cadmium (Cd) are set at 1.5, 0.5, and 15 mg/kg/day, correspondingly, as per USEPA (2002) (Cancer 2011; Fantke et al. 2012). The CR is calculated using the following formula:

$$CR_i = CSF_i \times CDI_i$$

$$CR = \sum_{i=1}^n CR_i$$

The FAO (2014) and Yin et al. (2015) indicate that the acceptable lifetime CR ranges from 10^{-4} to 10^{-6} , with values greater than 10^{-5} suggesting a substantial risk exceeding 1 in 100,000 of cancer development (Yin et al. 2015; Ahmed et al. 2019a, b, 2020; Traina et al. 2019).

Statistical analyses

To check the normal distribution of the data, tests such as Shapiro-Wilk and Kolmogorov-Smirnov were applied. The relationships among study variables were examined through correlation analysis, considering a statistical significance threshold of $p < 0.05$. Cluster analysis (CA), was employed to discern the intrinsic structure of the dataset without preconceptions about the data. This approach allows for the grouping or classification of elements in the system based on their similarity or proximity (Varol and Sen 2009). Hierarchical clustering, a prevalent CA method, initially pairs the most closely associated items and incrementally forms larger clusters. A “distance” between analytical parameters of samples is often characterized using Euclidean distance, indicating similarities (Otto 1998). In this study, hierarchical agglomerative CA was performed using Ward’s method and Euclidean distances as resemblance metrics (Ward 1963). This technique aims to curtail the within-cluster sum of squares at each combination step, using analysis of variance to assess the

distances between clusters. The relationship distance on the y-axis is uniformly depicted as the Dlink/Dmax ratio. This is equal to one hundred times the maximum distance divided by the total linkage distance for all circumstances (Shrestha and Kazama 2007; Varol and Sen 2009). SPSS (V.22) was used to execute these analyses (Bhuyan et al. 2023).

Results and discussion

Concentrations of heavy metals in sediment

Suppl. material 1: table S1 presents the results of an analysis of HMs concentrations (Cr, Ni, Cu, Mn, Fe, Zn, and Pb) in the top layer of sediments from the west coast of SMI. The observed higher concentrations of Mn and Fe, compared to other metals, are attributed to the reduced water flow in the sediment, potentially leading to HM accumulation (Bhuyan et al. 2017; Islam et al. 2020). Various sources contribute to the metal content in the sediments, including discharges from trawlers, gum boats, motorboats, and ships as well as agricultural and urban runoff (Devault et al. 2017). Furthermore, two proximate industrial facilities in Cox's Bazar and Chittagong might also be contributing to the metal levels (Deeba et al. 2021). Across twelve sampled locations, the HM concentrations in the sediment were found to be in the following order, from highest to lowest: Mn > Fe > Ni > Zn > Cr > Pb > Cu.

Chromium (Cr)

Cr, sourced from both natural and human activities like stainless-steel production and shipbreaking (Mohiuddin et al. 2011; Genchi et al. 2021), persists in water sediments and soil (Maurya and Kumari 2021). Cr (VI) is highly toxic, potentially causing liver, kidney, and lung damage, as well as severe gastrointestinal issues (Martin and Griswold 2009). The average Cr concentration was 12.17 ± 3.18 mg/kg, with a range of 7.22 to 17.61 mg/kg. S5 reported the highest level, 17.61 mg/kg. S1 recorded a minimum of 7.22 mg/kg. All of the sites had metal concentration values that were lower than those advised by the WHO (2004), and USEPA (1999). At the Sitakunda Shipbreaking area, Ali et al. (2022b) found a high amount (121.9 mg/kg) of Cr. Islam et al. (2022) observed 48.8 mg/kg Cr in Sundarbans sediment, which is significantly more than the present study (Suppl. material 1: table S2). Adani et al. (2022) on the coast of India discovered 6.48–8.86 mg/, while Yang et al. (2022) in the Coastal Pearl Bay of China discovered 35.8 mg/kg (Suppl. material 1: table S2). However, the concentration of Cr was investigated by Rahman et al. (2022a) in Nijhum Dweep who reported 7.20 mg/kg which was lower than our result. Nearly all of the results presented in Suppl. material 1: table S2 are higher than the results of the present study.

Copper (Cu)

Cu, used in both industry and farming (Yunus et al. 2020), is essential for hemoglobin formation and enzymatic reactions but can cause health issues at high concentrations (Singh et al. 2011; Al-Fartusie and Mohssan 2017). As a result of recent anthropogenic inputs from source sites, the Cu concentrations along the west coast of SMI range from 3.14 to 6.41 mg/kg with an average

value of 5.16 mg/kg (Suppl. material 1: table S2). At S5, the maximum Cu value (6.41 mg/kg) was reported, whereas the lowest Cu concentration (3.14 mg/kg) was reported from S10. Concentrations of Cu along the west coast of SMI are below the background reference value at all locations (Turekian and Wedepohl 1961; USEPA 1999). In contrast, higher Cu was reported in the sediments of Nijhum Dweep (Rahman et al. 2022a) and the Sundarbans (Islam et al. 2022) (Suppl. material 1: table S2). This was thought to be a possible source of industrial effluent and extreme usage of disinfection chemicals in aqua-culture that eventually discharged into water bodies (Barg 1992). Other studies have demonstrated that contamination of Cu is related to ship construction and maintenance (Fan et al. 2022).

Nickel (Ni)

Ni, a non-biodegradable hazardous HM found in wastewater (Kanwar et al. 2020), comes from both natural sources like rock weathering and volcanic emissions (Cempel and Nikel 2006) and human activities such as shipbuilding, stainless steel production, and electroplating (Neves et al. 2020). Exposure to Ni can cause harmful effects including dry cough, lung cancer, chest pain, and nausea (Yunus et al. 2020). In this study, the concentration of Ni varied between 16–36 mg/kg, with an average of 24.17 mg/kg, as shown in Suppl. material 1: table S2. The highest and lowest Ni concentrations were observed in samples S5 and S1, respectively. Hasan et al. (2020) reported Ni concentration of 54.2 mg/kg in the sand at the Sitakunda Shipbreaking site. Hossain et al. (2019) and Kabir et al. (2018) found Ni concentrations of 32.8 mg/kg in the sediment of the Sangu River estuary and 16.0 mg/kg in the Sonadia Island sediments respectively (Suppl. material 1: table S2). Notably higher Ni levels were recorded in the Hong Kong coast's sediment and Tunisia's South Lagoon (Abidi et al. 2022; Huang and Chen 2022).

Manganese (Mn)

During crustal weathering, Mn can be obtained from a terrestrial source and transformed into intricate hydroxyl manganese compounds that precipitate into the sediments (Wedepohl 1995). Mn values in this study ranged from 226 to 395 mg/kg with a mean of 317.58 mg/kg (Suppl. material 1: table S2). S11 had the highest concentration (395 mg/kg), whereas S1 had the lowest concentration (226 mg/kg). Mn concentration of 390.7 mg/kg was found in the silt collected from Sonadia Island (Kabir et al. 2018) (Suppl. material 1: table S2). In contrast, at the Sitakunda Ship-breaking area, Hasan et al. (2020) recorded Mn concentration of 1084.7 mg/kg. Abidi et al. (2022) found lower Mn levels in the South Lagoon sediment (Tunisia).

Zinc (Zn)

Zn, found in the earth's crust and more associated with mud and organic debris than sand (Anbuselvan and Sridharan 2018), is released into the environment by industrial activities like brass plating, paper manufacturing, and galvanizing (Yunus et al. 2020). While essential for various physiological processes (Kambe et al. 2015), excessive Zn can cause health issues such as stomach pain, skin rashes, and anemia (Yunus et al. 2020). In the present study, Zn concentrations

ranged from 22 to 42 mg/kg with an average value of 31.17 mg/kg, which is lower than reported in other studies (Suppl. material 1: table S2). The Zn content along the west coast of SMA was below the recommended geochemical concentration and sediment quality guideline index. The highest and lowest Zn concentrations were reported at S11 and S1 respectively. In contrast, Zn concentrations in sediments at the Sitakunda Shipbreaking location have Zn concentrations as high as 1226.3 mg/kg (Hasan et al. 2020) (Suppl. material 1: table S2), while the Sonadia Island's sediment contained 38.75 mg/kg (Kabir et al. 2018).

Lead (Pb)

Pb, a stable and highly harmful element to both humans and animals (Giannakoula et al. 2021), primarily enters the marine system through air deposition and coal-burning fly ash (Whiteside and Herndon 2019). Found in higher concentrations in mud and surface sediments, Pb is a non-essential metal that poses risks to human kidneys and nervous systems (Anbuselvan and Sridharan 2018; Fasae and Abolaji 2022). Pb concentration along the west coast of SMI ranged from 5.15 to 8.75 mg/kg, with an average of 6.52 mg/kg (Suppl. material 1: table S2). The highest concentration was recorded at site S11, while the lowest was found at site S7. Compared to other regions in Bangladesh, the west coast of SMI has much lower Pb concentrations (Ali et al. 2022; Islam et al. 2022; Rahman et al. 2022b; Rakib et al. 2022). Hasan et al. (2020) reported 68.3 mg/kg Pb in the sediments of the Sitakunda Shipbreaking area (Suppl. material 1: table S2).

Iron (Fe)

Fe, primarily formed by crust weathering, can form complex hydroxyl compounds that may precipitate into sediments (Gopal et al. 2022). Its positive association with mud suggests that mud plays a major role in controlling Fe's spread, and Fe_3O_4 may also cause the coprecipitation of other HMs in sediments (Boughriet et al. 2007). The concentration of Fe along the west coast of SMI ranged between 110–240 mg/kg with an average of 168.42 mg/kg. Sediments in sites S11 and S8 contained the highest and lowest Fe concentration respectively. These concentrations are lower than the findings in other studies (both national and international). Islam et al. (2022) reported Fe concentrations of 38432.5 mg/kg in the sediments of Sundarbans, while Rakib et al. (2022) reported Fe concentrations of 31658 mg/kg in the sediments of Hatiya and the ship-breaking yards. Some of the highest Fe concentrations, 93015.1 mg/kg and 62990–75210 mg/kg, were recorded in the sediment of the Shipbreaking area (Rahman et al. 2019; Hasan et al. 2020).

Assessment of sediment contamination levels

$$I_{\text{geo}}$$

The sequence of HM contamination levels in the study area, as per average I_{geo} values, is $\text{Mn} (-2.02) > \text{Ni} (-2.12) > \text{Pb} (-2.22) > \text{Zn} (-2.22) > \text{Cr} (-3.52) > \text{Cu} (-3.74) > \text{Fe} (-8.74)$. Mn exhibited the maximum I_{geo} , while iron had the lowest. According to the negative I_{geo} values (Fig. 2), the sampling sites along the west coast of

SMI indicated very low or no significant metal contamination. Minor variations in metal levels were noted across the sample sites, impacting the Igeo values. For all metals examined, including Cu, Cr, Zn, Pb, Mn, Ni, and Fe, the negative Igeo values in the study area suggested an absence of pollution. Bhuyan et al. (2023) recorded Igeo values in the subsequent order: Mn > Ni > Pb > Zn > Cr > Cu > Fe in the sediment of Eastern SMI. In contrast, Igeo values for the Liaohe River reserve, as reported by Ke et al. (2017), fell into the highly polluted category. Mohiuddin et al. (2011) showed that Igeo values for Pb and Cu were still classified as unpolluted at River Turag. The higher metal contributions in the Liaohe and Turag rivers, compared to the present study, were primarily responsible for these differences.

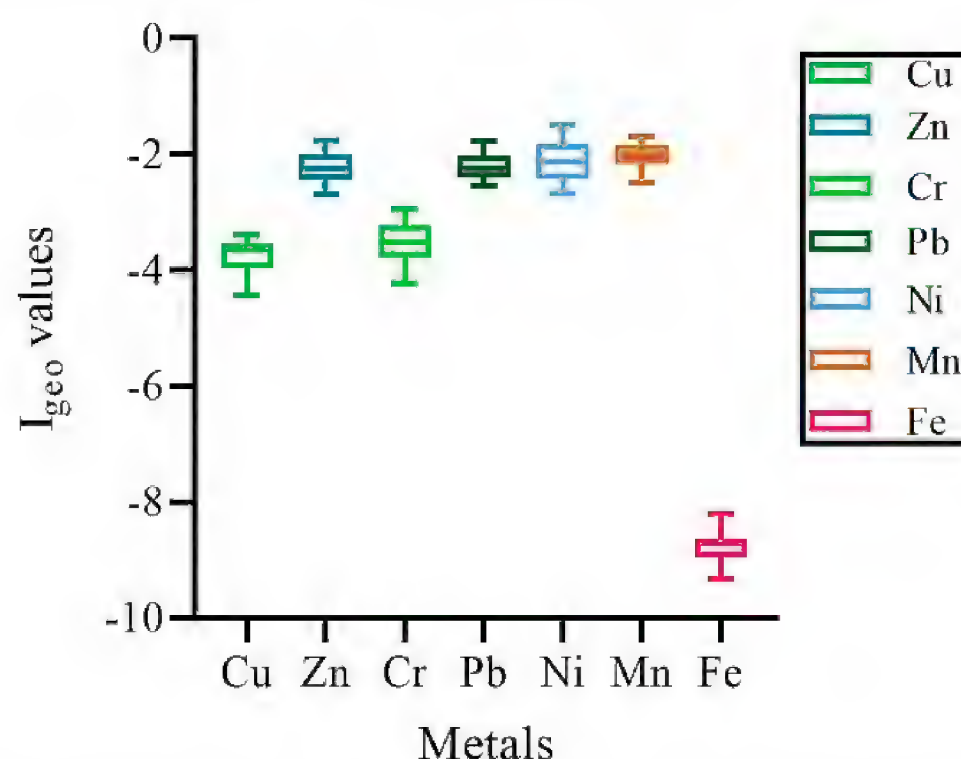


Figure 2. Igeo for the metal contents investigated in the sediments along the west coast of St. Martin's Island.

Evaluation of CF and PLI

Fig. 3 displays the CF values for various metals, categorized as follows: Pb varies from 0.26 to 0.44 (average 0.33 ± 0.05), Cr from 0.08 to 0.20 (average 0.14 ± 0.04), Cu from 0.50 to 1.21 (average 0.76 ± 0.21), Zn from 0.23 to 0.44 (average 0.33 ± 0.07), Ni from 0.24 to 0.53 (average 0.36 ± 0.09), Mn from 0.27 to 0.46 (average 0.37 ± 0.06), and Fe from 0.002 to 0.01 (average 0.004 ± 0.001) as illustrated in Fig. 3. The results show that sites S6 and S10 exhibited moderate contamination by Cu, with CF values of 1.03 and 1.21, respectively. The overall mean CF value for the area was below 1, suggesting the absence of contamination from the metals. Bhuyan et al. (2023) reported similar findings in the Eastern SMI, Bangladesh. Doulah et al. (2017) stated that CF values showed low to moderate pollution in the coastal area of Kutubdia Island, Cox's Bazar, Bangladesh. Additionally, the PLI calculations indicated no pollution in the area, as all PLI values were below 1. PLI values remained below 1, indicating a reduction in baseline pollution levels across all sites of SMI (Sarker et al. 2020). Contrasting these findings, a study by Islam et al. (2015) reported different results for an urban river in Bangladesh. Their research attributed a high concentration of HMs in sediment to domestic sewage, industrial effluents, and atmospheric deposition. Similarly, findings by Hassan et al. (2015) on the Meghna River diverged from the observations of this study.

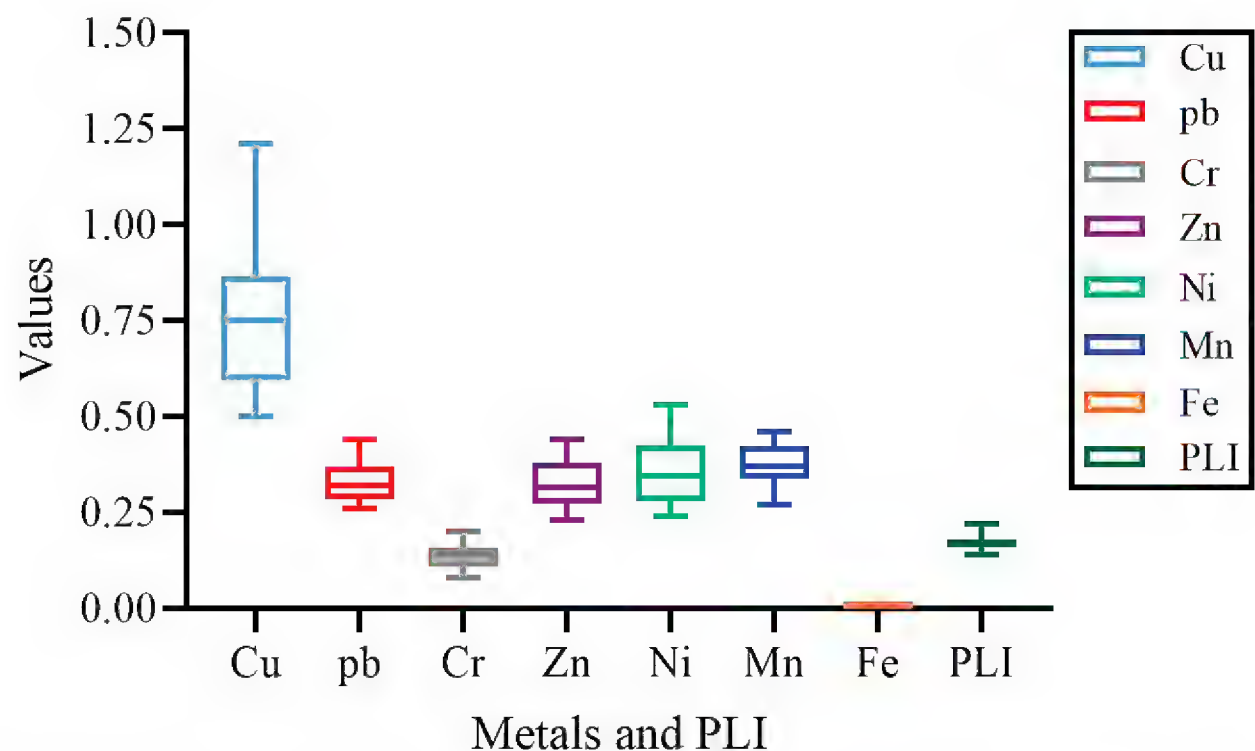


Figure 3. Contamination factor (CF) and pollution load index (PLI) in the sediment samples from the west coast of St. Martin's Island.

Evaluating PERI

We evaluated PERI and all the distinguishing characteristics that highlighted the combined eco-toxicological impacts of several aquatic environment pollutants using a single-factor ecological risk model (Karydas et al. 2015). For all metals, the monomial PERI was determined to be minimal at every location. All metals' PERI values across all locations were within acceptable limits. All metals in the research region had PERI scores that varied from 0.23 to 2.65, which means there is no environmental risk (Fig. 4). The present findings are quite similar to the study of Bhuyan et al. (2023) in the Eastern part of the Island. Due to the Cd input, two sites (sites 1 & 13) had their PERI rated in a moderate-risk zone (Sarker et al. 2020). Extensive high-resolution sediment core samples confirmed to the fact that natural and human factors both contribute to possible ecological danger to the coastal ecosystem (de Silva et al. 2022). The sites were rated in decreasing order based on the Risk Index (RI) values for the cumulative metal values: S11 > S5 > S8 > S12 > S9 > S3 > S6 > S7 > S4 > S2 > S1 > S10 and the values ranged from 3.86 to 6.18 (Fig. 4). All the PERI and RI findings did not surpass the low-mod-

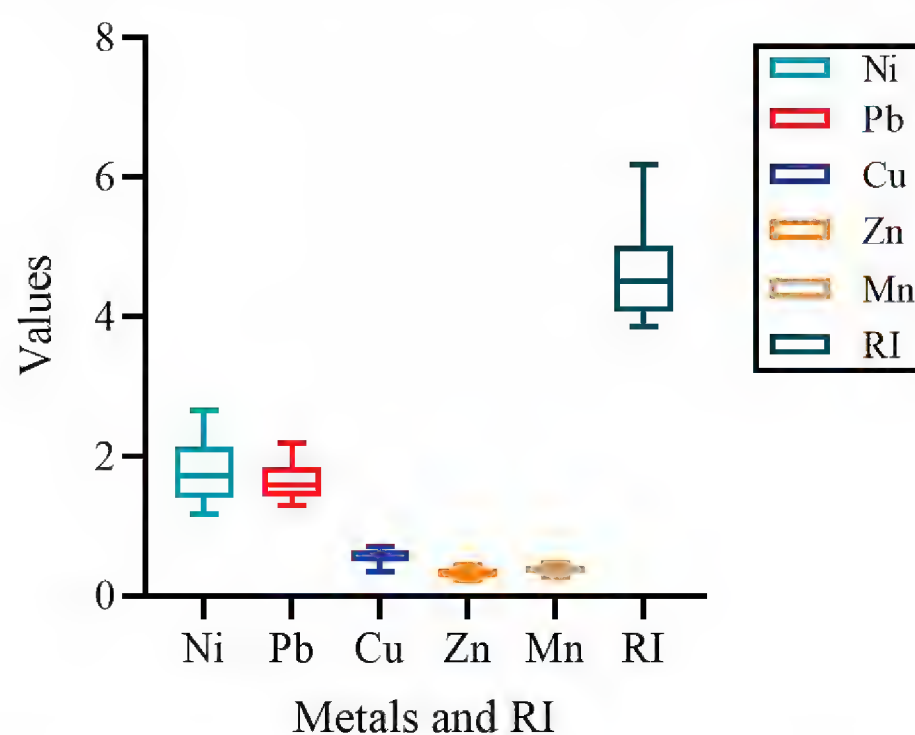


Figure 4. Potential ecological risk index (PERI) in the sediments along the west coast of St. Martin's Island.

erate risk line. Thus, it was determined that there was no harm to the aquatic ecosystem in the study region. However, with rapid urbanization and industry development adjacent to the coastal areas, more ecological elements must be continuously checked to assess the quality of sediments (Xia et al. 2018).

Human health risk assessment

The danger to human health was examined since the local communities in the study area were involved in growing a range of seasonal crops. The bulk of the residents used the silt from the island for their agricultural plots. According to El-Alfy et al. (2021) and Chonokhuu et al. (2019) the fundamental idea and method for understanding harmful impacts on the human body and exposure to ecological dangers is risk assessment. Three major pathways' risk to human health was evaluated using the following methods:

Estimating CDI

In the areas under investigation, the computed daily intakes (CDIs) of metals for both adults and children are shown in Table 3. ingestion > dermal > inhalation were the exposure pathways that reduced, according to the research, with CDIs being greater in children than in adults. Sharma et al. (2005) also reported the same in Kanpur, India. Table 3 shows exposure paths, Cr showed the highest CDI values among the investigated metals for both children and adults. The dermal exposure route depicted an average child's CDI value of $2.90\text{E-}06$ and adults of $4.42\text{E-}07$. The maximum ingestion CDI was also observed among children ($2.03\text{E-}03$) compared to adults ($4.35\text{E-}04$) resulting in elevated levels of Mn. In terms of inhalation, the maximum value was for Mn for both children ($1.08\text{E-}06$) and adults ($2.31\text{E-}07$) (Table 3). Similar results were stated by Bhuyan et al. (2023) in the Eastern part of SMI.

Assessing THQ

The mean CDI values were utilized to evaluate the non-carcinogenic risk. For both age groups, the ingestion method's Cr metal concentration had the highest HQ value ($1.40\text{E-}02$ for adults and $2.59\text{E-}02$ for children) (Table 3). Additionally, Cr showed that all sorts of persons occupied a significant role, although Cr had a greater attribution to HQ when using the strategy of inhalation (Table 3). For all nearby local community paths, the overall HQ outcomes were observed in the order shown below: Cr > Mn > Pb > Zn > Ni > Fe > Cu. The evaluation of HI involved measuring HQ. According to Table 3, the average HI for children and adults was $9.61\text{E-}03$ and $4.00\text{E-}03$, respectively. Additionally, the five-component HI as a whole showed that children were more susceptible than adults. The study location did not have a substantial non-carcinogenic risk effect, according to the overall findings of 1. Similar results were demonstrated by Bhuyan et al. (2023) in the Eastern SMI. Three fish species and one crab species were found to have acceptable carcinogen ranges collected from SMI (Baki et al. 2018). Similar conclusions were made on the Yangtze River, where residents were kept from going above the disturbing level of $\text{HI} < 1$ (Hu et al. 2017). Similar conclusions were reached by Ahmed et al. (2020) in the Gomti river of Bangladesh.

CR evaluation

The USEPA has not given a carcinogen CSF for Pb, but it did estimate the carcinogenic risk (CR) for Cr. Table 3 displays the CR findings. Both adults and children most commonly encountered the three exposure routes through ingestion. For instance, the CRs of certain metals for distinct age groups may differ significantly (Table 3). Children generally had higher average CR values (1.30E-05) than adults (2.79E-06), according to the results (Table 3). Additionally, children were exposed to higher CR in terms of Cr through the ingestion route, which had a greater impact compared to other components. From Table 3, the Cr total TCR was examined and was found to be 3.91E-05 in children and 8.38E-06 in adults, which was below the threshold range of (10^{-4} to 10^{-6}). The result suggests the area is unlikely to pose a carcinogenic risk. The carcinogenic effects of metals via the skin and respiratory systems were found to be within reasonable limits for both adults and children (El-Alfy and Elnaggar 2023). However, children were more susceptible to the CR effect compared to adults. El-Alfy et al. (2021) from the Burullus Lake silt, discovered that children were more susceptible to the CR when ingesting metals than adults. Cd, Cr, Pb, and As lifetime carcinogenic risk (LCR) values on sand taken from Bangladeshi coastal areas indicated lower carcinogenic risk ($LCR < 10^{-4}$) (Raknuzzaman et al. 2016).

Table 3. Metal contents human health risk assessment in the sediment of Western St. Martin’s Island.

Metals	CDI	HQ						HI	CR			TCR
Adults	Inhalation	Dermal	Ingestion	Inhalation	Dermal	Ingestion			Inhalation	Dermal	Ingestion	
Cr	8.84E-09	6.65E-08	1.67E-05	2.95E-06	2.22E-05	5.56E-03	5.58E-03		4.42E-09	3.33E-08	8.34E-06	8.38E-06
Pb	4.73E-09	3.56E-08	8.93E-06	1.35E-06	1.02E-05	2.55E-03	2.56E-03					
Cu	3.74E-09	2.82E-08	7.06E-06	9.36E-08	7.05E-07	1.77E-04	1.77E-04					
Zn	2.26E-08	1.70E-07	4.27E-05	1.13E-06	8.52E-06	2.13E-03	2.14E-03					
Mn	2.31E-07	1.74E-06	4.35E-04	1.65E-06	1.24E-05	3.11E-03	3.12E-03					
Ni	1.75E-08	1.32E-07	1.54E-04	1.60E-06	1.20E-05	1.40E-02	1.41E-02					
Fe	1.22E-07	9.21E-07	2.31E-04	1.75E-07	1.32E-06	3.30E-04	3.31E-04					
Children												
Cr	4.12E-08	4.36E-07	7.78E-05	1.37E-05	1.45E-04	2.59E-02	2.61E-02		2.06E-08	2.18E-07	3.89E-05	3.91E-05
Pb	2.21E-08	2.33E-07	4.17E-05	6.31E-06	6.67E-05	1.19E-02	1.20E-02					
Cu	1.75E-08	1.85E-07	3.30E-05	4.37E-07	4.61E-06	8.24E-04	8.29E-04					
Zn	1.06E-07	1.12E-06	1.99E-04	5.28E-06	5.58E-05	9.96E-03	1.00E-02					
Mn	1.08E-06	1.14E-05	2.03E-03	7.69E-06	8.12E-05	1.45E-02	1.46E-02					
Ni	8.19E-08	8.65E-07	4.27E-05	7.44E-06	7.86E-05	2.13E-03	2.22E-03					
Fe	5.71E-07	6.03E-06	1.08E-03	8.15E-07	8.61E-06	1.54E-03	1.55E-03					

Identification of heavy metals sources in sediment

Shapiro-Wilk and Kolmogorov-Smirnov tests exposed that the HM concentrations in the sediments were normally distributed. Additional statistical studies were conducted using Correlation Matrix (CM), PCA, and CA to provide some prospects that gave some related possibilities such as pollution sources, correlation of metal contents, etc. (Bhuyan et al. 2019; Bhuyan et al. 2023).

The Pearson correlation matrix demonstrated the relationships between the metals (Ahmed et al. 2019a). The correlations among the metals can be positive and/or negative (Ahmed et al. 2022). Metal such as Cr-Ni ($r=0.986$), Cr-Mn ($r=0.854$), and Ni-Mn ($r=0.806$) depicted a robust positive correlation at the alpha level of 0.01 (Table 4). Bhuyan et al. (2023) reported that very high positive correlation between Cr and Mn ($r = 0.960$) at the alpha level 0.01. Cr displayed a very noteworthy positive association with Mn ($r = 0.592$, $P<0.01$) (Khallaf et al. 2021). In addition, Cr-Zn ($r=0.697$), Cr-Fe ($r=0.650$), Ni-Zn ($r=0.644$), and Ni-Fe ($r=0.606$), Mn-Zn ($r=0.594$), Mn-Pb ($r=0.544$), Mn-Fe ($r=0.635$), and Pb-Fe ($r=0.610$) exhibited significant positive correlation ($p<0.05$). Moreover, metal pairs including Cr-Pb ($r= 0.429$) and Cu-Pb ($r=0.403$) depicted a weak relationship (Table 4).

Table 4. Correlation and PCA.

	Cr	Cu	Ni	Mn	Zn	Pb	Fe	PC1	PC2
Cr	1							0.474	-0.103
Cu	0.310	1						0.158	0.630
Ni	0.986	0.312	1					0.458	-0.092
Mn	0.854	0.098	0.806	1				0.443	-0.106
Zn	0.697	-0.097	0.644	0.594	1			0.328	-0.526
Pb	0.429	0.403	0.403	0.544	0.036	1		0.299	0.525
Fe	0.650	0.188	0.606	0.635	0.379	0.610	1	0.384	0.142
Eigenvalue								4.14	1.35
% of Variance								59.11%	19.25%
Cumulative % of Variance								59.11%	78.36%

The qualitative grouping tendency of several features such as metal correlation and sources was evaluated using PCA. Fig. 5 displays the PCA outcomes for each item with an eigenvalue greater than one and a total variance of 78.36%. The PCA findings for every factor with a cumulative variance of 80.56% and an eigenvalue greater than one (Bhuyan et al. 2023). The PCA examined the two grouping components. PC1 and PC2 contributed 59.11% and 19.25% of the overall variation, respectively. The loadings of 0.474 and 0.458 for Cr and Ni, dominated PC1, while 0.630 and 0.525 for Cu and Pb, respectively, dominated PC2 (Fig. 5). The findings showed that PC1, including manufacturing companies and refineries, originates from both human and geogenic causes (Shikazono et al. 2012).

According to Yang et al. (2009) and Sundaray et al. (2011), one cluster showed a certain set of locations for locating contaminated sites, whereas a separate cluster showed a different set of locations. The clusters were identified using Euclidean distance and Ward Linkage (Ahmed et al. 2019a, b). Cluster analysis at $(Dlink/Dmax) \times 100 < 0.6$ (Chung et al. 2011) was used to investigate the connection between the evaluated metals and likely sources. Three clusters were created horizontally by the dendrogram. Cr, Ni, Mn, and Zn made up Cluster 1, Cu made up Cluster 2, while Pb and Fe made up Cluster 3 (Fig. 6). This means that these elements exhibited similar patterns or compositions in the analyzed samples and were grouped based on their similarities. Also, a substantial cluster at $(Dlink/Dmax) \times 100 < 100$ and four prominent clusters were shown on the dendrogram created by the CA for sample sites: cluster 1, cluster

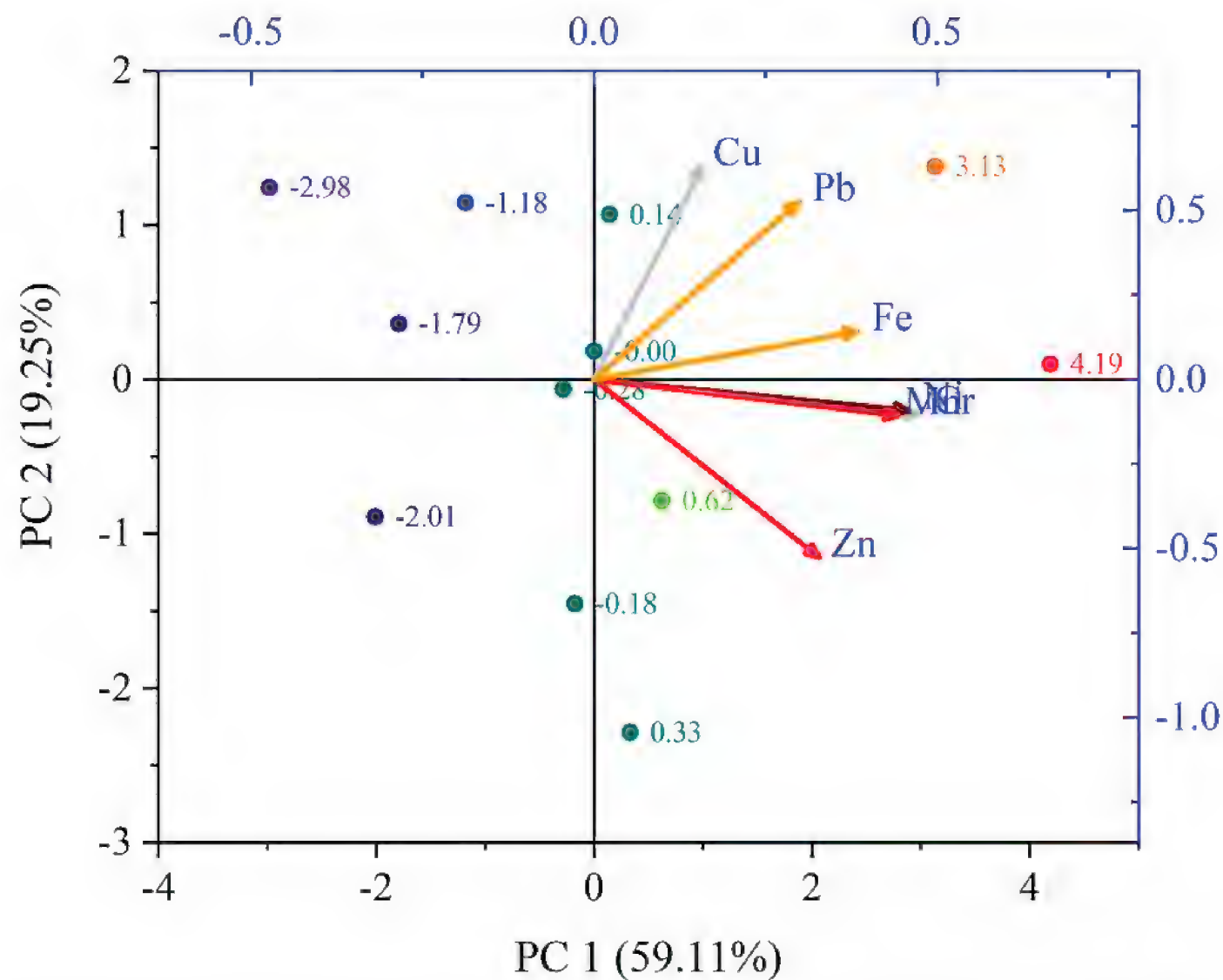
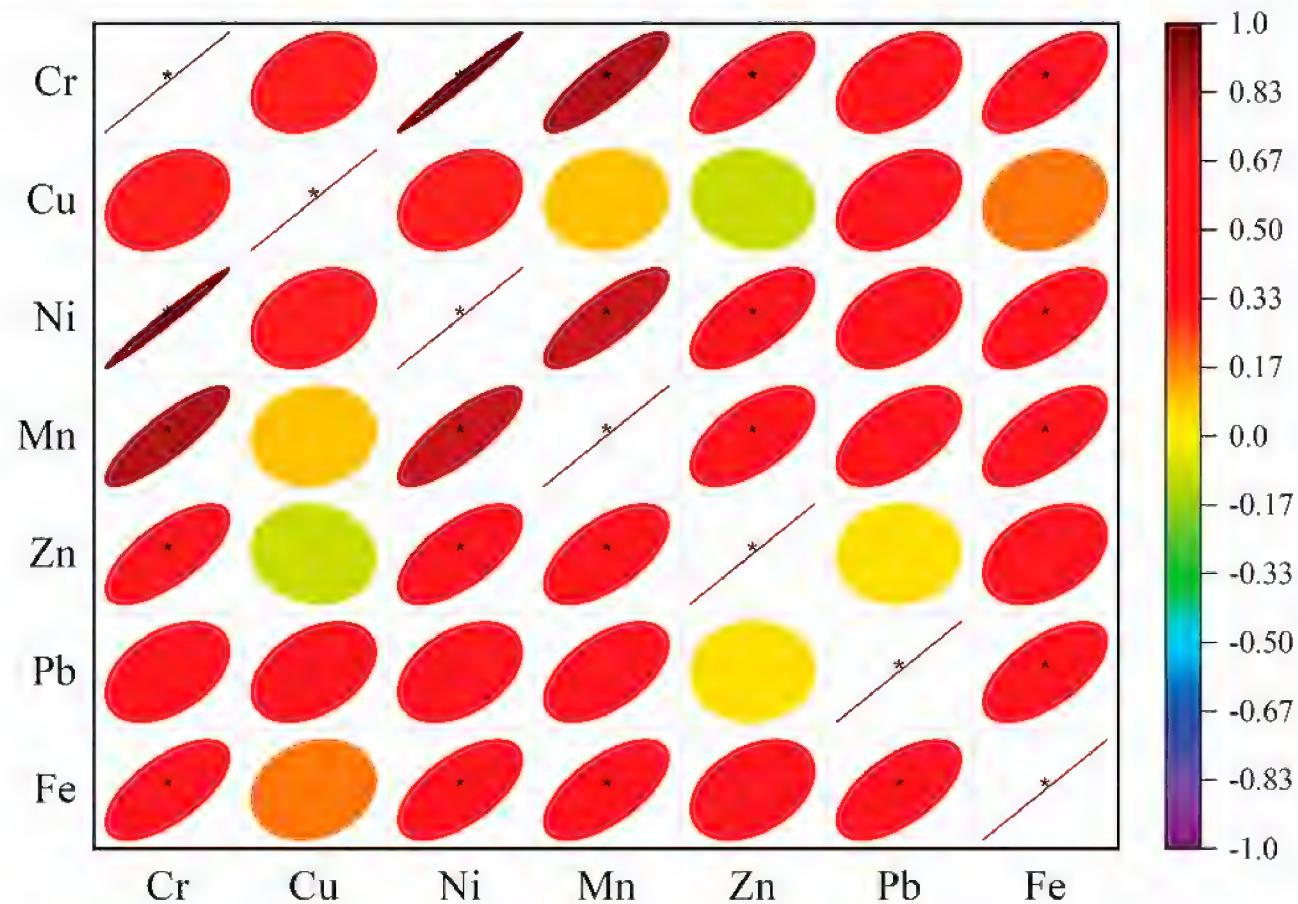


Figure 5. PCA results of the metals in the sediments along the west coast of St. Martin’s Island.



* $p \leq 0.05$

Figure 6. Hierarchy dendrogram showing the relationship of HMs in sediments along the west coast of St. Martin’s Island.

2, cluster 3, and cluster 4. Sites S1, S2, and S4 were in Cluster 1; Sites S3, S9, S10, S6, and S7 were in Cluster 2; Sites S8, and S12 were in Cluster 3; and Sites S5, and S11 were in Cluster 4 (Fig. 6). Almost similar findings were recorded in the eastern SMI by Bhuyan et al. (2023). This information indicates that the

cluster analysis identified similarities or patterns among the sample sites, leading to the grouping of certain sites together based on their characteristics or attributes (metal concentration).

Conclusions

The findings of the current study designate that HM concentrations in marine sediments along the west coast of SMI do not pose a severe danger to marine life and the human body. Among the HMs, Mn and Fe were at higher concentrations than others but remained within acceptable range. The concentration of HMs in the sediments was within permissible limits but lower when compared to other regional, national, and global data. Various indices suggest that the sediments along the west coast of SMI are not contaminated, making it a suitable habitat for aquatic life. Children are more vulnerable to potential hazards from HM contamination than adults. However, there was no evidence for non-carcinogenic and carcinogenic effects on the local community. The study recommends considering the chemical fractionation of sediments for a more accurate and precise assessment of the risks posed by HMs, and the pathways of their distribution in marine ecosystems. Additionally, the development and implementation of an environmental monitoring program on SMI is recommended to detect future environmental impacts, such as metal contamination, and to ensure the preservation of its environmental health. The study emphasizes how crucial ongoing observation and flexible management are in maintaining SMI's ecological health. Dedication to future science-based studies is essential to guarantee the environmental viability of this maritime ecosystem for forthcoming generations. Additionally, monitoring of metal attribution in the study area should be monitored accordingly.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

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Author contributions

Md. Simul Bhuyan: Conceptualization, Supervision, Writing-original draft, review & editing, visualization. Muhammad Abu Bakar: Analysis, Review & editing. Gowhar Meraj: Review & editing. Mrityunjoy Kunda: Review & editing. Mir Mohammad Ali: Statistical analysis, Review & editing, visualization. Md. Tarikul Islam: Review & editing. Nazmul Hossain: Review & editing, visualization. Ranjan Roy: Review & editing, visualization. Dinesh Chandra Shaha: Review & editing. Stanley Iheanacho: Review & editing. Lamjed Mansour: Review & editing. Lotfi Jilani Rabaoui: Review & editing. Davide Di Paola: Review & editing.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Supplementary tables S1, S2

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Data type: docx

Explanation note: **table S1**: Heavy metals in beach sediment of Western St. Martin's Island; **table 2**: Comparison of present findings with national and international findings.

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